A Study of Radiative Heat Transfer Through Greenhouse Covering Materials

著者	Almahdouri Adil Abdullah Humaid
号	58
学位授与機関	Tohoku University
学位授与番号	工博第004893号
URL	http://hdl.handle.net/10097/58883

	アルマハドウリ　アデル　アブドウラ　ホメイド
氏　　　　　名	Al Mahdouri Adil Abdullah Humaid
授　与　学　位	博士（工学）
学位授与年月日	平成２６年３月２６日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）機械システムデザイン工学専攻
学位論文題目	A Study of Radiative Heat Transfer Through Greenhouse Covering Materials （温室用被覆材におけるふく射伝熱に関する研究）
指　導　教　員	東北大学教授　圓山　重直
論文審査委員	主査　東北大学教授　圓山　重直　東北大学教授　湯上　浩雄 東北大学教授　小原　拓　東北大学准教授　小宮　敦樹 講師　伊吹　竜太（宮城大学）　東北大学助教　岡島　淳之介

論文内容要旨

There is a scarcity of information about effect of the greenhouse covering material on heat trapping. Generally, few experimental and theoretical studies assessed of the difference of infrared absorbing and infrared-transparent materials on greenhouse effect. According to literatures, still no one has studied the absorptivity and reflectivity of the covering materials on the using a nongray study for the full radiations spectrum ranged between the ultraviolet to mid-infrared. Therefore, the current study describes a study on radiative heat transfer through greenhouse covering materials. In order to verify the contribution of covering material on heat trapping and rising the temperature inside a greenhouse, this thesis describes the radiative heat effect explained in six main chapters. Each chapter is outlined as the following;

Chapter 1: General introduction and background

Chapter 1 is includes a background of this study. A brief discussion about the necessity of radiative heat transfer control and its wide area of applications has been presented. A rapid review of the past researches on "heat transfer control laboratory" regarding to control of radiative heat transfer has been also mentioned. An introduction discusses about the "Greenhouse Effect" and the debate on "heat trapping" caused by the greenhouse covering materials is explained. World climatic zones categorization is described. After that, available heating and cooling systems are verified for agricultural greenhouses. General review about past studies on predicting the optical properties of the greenhouse covering materials such as glass and plastics were briefly explained at the end of this chapter. Finally, "Greenhouse Effect" assessment methodology is proposed by using a nongray radiative model. This will be studied by estimating the spectral radiative properties of a greenhouse claddings and, then, applying a nongray rigorous model to find the thermal performance of each cladding.

Chapter 2: Theoretical Modeling of Radiative Heat Transfer in A Transparent Media

In this chapter, the radiative properties of a semi-transparent material were briefly discussed. Principles of ray tracing, transmissivity, reflectivity and absorptivity of a semi-transparent material are discussed. Moreover, the reflectivity and transmissivity of thin metallic film coating on a cladding material was discussed. The net radiation method is discussed for estimating the reflectivity and transmissivity of solar radiation a plane and coating semi-transparent materials. After that, the Radiation Element Method by Ray Emission Model (REM^2) is explained in details as one of recommended radiative models. The ray emission model is explained as the main core of REM^2. The advantage of using REM^2 on thermal studies is represented in the involvement of absorption and emission within the covering materials was illustrated. Moreover, the specular reflectivity at the vicinity of the covering material was considered. Then, REM^2 in one-dimensional plane parallel system was clarified for radiative heat transfer analysis. This model was used for the radiative heat transfer through semi-transparent slabs.

Chapter 3: Evaluation of Spectral Radiative Properties of Greenhouse Covering Materials

This chapter focused on evaluating of the spectral radiative properties of common greenhouse covering materials which are widely used. A new integrated inverse method was implemented to evaluate the spectral indices of refraction for several greenhouse transparent and semi-transparent greenhouse roofs. This method consisted of measuring the spectral normal transmittance and diffuses reflectance of the covering materials in the region between UV-IR radiations. After that, the Jacobian matrix was established consisting of the differential change of the measurements to change of the real and imaginary parts of the spectral indices of refraction. The inverse method was applied using Newton-Raphson method on the previously mentioned REM^2. In order to validate the inverse, it was applied on well-known low density polyethylene (LDPE). Full spectrum measurements of normal transmittance, diffuse reflectance of the plastic film over a black substrate and the black substrate for 50μm thick LDPE film are shown in Fig.1. Those measurements were used in in the inverse REM^2 to find the real and imaginary parts of the indices of refraction, shown in Fig.2. Those results had shown good agreement with reference values. In addition to LDPE, full spectrum optical properties of several plastic materials were predicted. Examples of these plastic films were polyvinylchloride (PVC), polyolefin (PO), poly tetrafluoroethylene (PTFE), poly ethylene terephthalate (PET) and ethylene tetrafluoroethylene (ETFE).

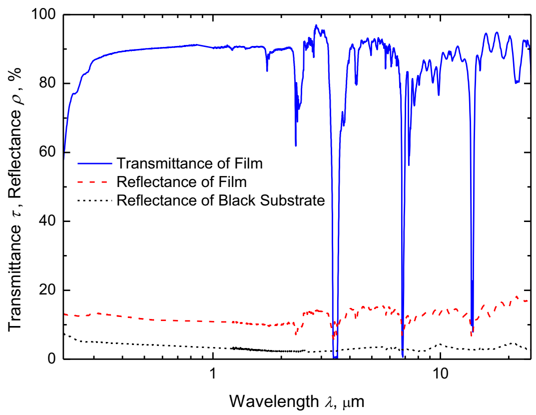

Fig 1. Spectral transmittance and reflectance of LDPE film

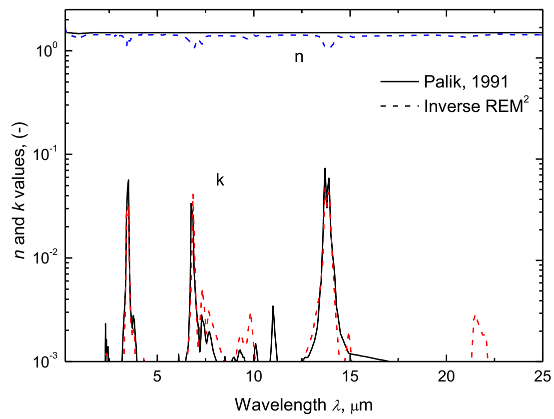

Fig 2 one dimensional One-dimensional plane-parallel analysis model

Furthermore, this method was applied to investigate the difference in products of similar material. This was applied to PVC products. Results showed good similarities in the calculated spectral indices of refraction. It was also suggested that coating a plastic film with low emissive metallic oxide thin film can increase the heat trapping inside the greenhouse. This is due to high reflectivity to IR radiation. Therefore, spectral indices of refraction were calculated for a polyethylene naphthalate (PEN) film that coated with thin indium tin oxide (ITO) film. Inverse REM^2 was also applied for silica glass in the solar radiation region (UV-NIR).

Additionally, the optical properties of opaque silica glass materials were obtained using inverse REM2 in the region from UV to NIR. However, in the infrared region (IR) Kramers-Kronig method was used. The Kramers-Kronig relations are based on the requirement of causality where n and k parts of a response function are always related through a dispersion relation. At room temperature, near-normal reflectance measurements are performed on the material slab from 0.2-25μm by utilizing the earlier integrating spheres for the ranges UV-VIS and NIR. After applying Kramers-Kronig method to measurements on silica glass material, the calculated indices of refraction using was also validated with reference data in the IR spectra.

Chapter 4: Greenhouse Thermal Performances for Different Covering Materials Using a Nongray Model

In this chapter, a nongray rigorous radiative model using REM^2 was established to precisely estimate the radiative heat transfer through greenhouse covering materials. This could be achieved using REM^2 for the full spectrum from UV to mid-IR region. The predicted optical properties of all given greenhouse materials were used. The calculations were executed to find the quasi-steady state temperatures of a greenhouse at day time; such as soil surface, inside air and covering sheet temperatures for identical greenhouses covered with the given covering materials. The solar irradiation model used in this study was the Bird's model. This calculation was applied for horizontal greenhouses (enclosures) at noon time and incident angle of 25^o. The steady state temperatures were found of all greenhouses, shown in Fig.3. Generally, the differences of greenhouses temperatures were found between all materials. Thus, the difference in heat trapping could be confirmed. The highest inside air temperature was found for PEN/ITO covered greenhouse. This was because of the significant contribution of IR reflection for the reemitted IR radiation from the soil surface.

When temperatures of those greenhouses were compared to the ones calculated for a superficial greenhouse covered with a non-absorbing cladding, the greenhouse effect was confirmed due to the reflectivity and absorptivity to IR radiations. For instance, the greenhouse effect was verified and the contribution of greenhouse covering sheet was confirmed of 21.4% when covered with silica glass. This was increased when applying of infrared reflective coating on PEN sheet to become 25.4% from the total contribution to temperature rising inside the greenhouse. Moreover, the cooling effect of ITO coated PEN film was evaluated. The difference in greenhouse inside air temperature showed a reduction of about 8.6°C in contrast to glass covered greenhouse.

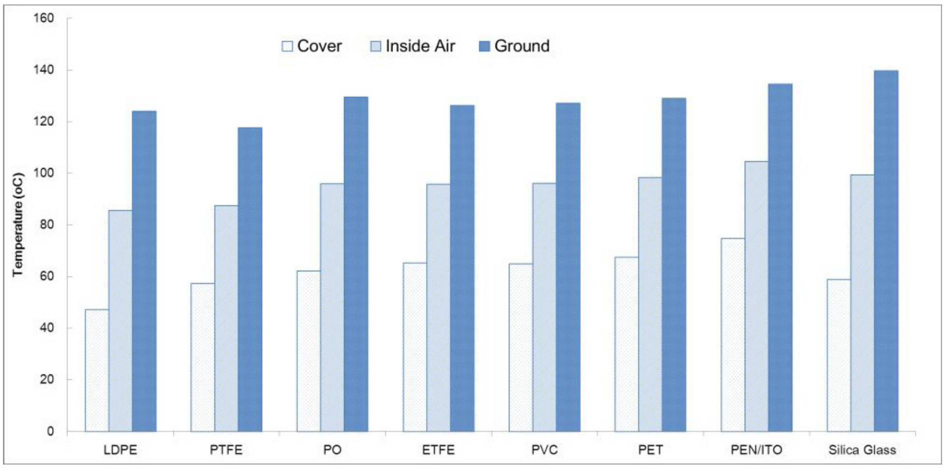

Fig.3 Steady state temperatures of number of greenhouses covered with different plastic films

The effect of sheet thickness has been investigated for above mentioned materials. The thickness can effect to on solar radiation transmittance by which heat input can reduces

The calculation was also applied for three enclosures covered with silica glass, PVC and LDPE, during a solar day (Jan. 31st, 2013) using measured temporal weather conditions. The absorption and emission within the covering material were taken into account. Moreover, the specular reflectivity and refraction at the boundary surface was treated at the cover surfaces. Enclosures were tilted with 35° from the ground. Calculation model is shown in Fig.4. In the same way, an outdoor experiment was conducted to evaluate the temperature inside enclosures. The temporal measurements of black surface (soil), inside air and film temperature were acquired for identical rectangular enclosures covered with silica glass, PVC and LDPE. There were good correlations between the measured temperatures and the corresponded ones found by the rigorous model. Furthermore, there is good agreements of the calculated and measured internal convective heat transfer coefficients. The differences in temperatures were also examined between three greenhouse enclosures roofed with different materials such as PVC, LDPE and silica glass. It is not only the solar heat source which can increase the greenhouse temperatures, but also the IR absorption and reflectance of the covering material play a contributive role on heat trapping.

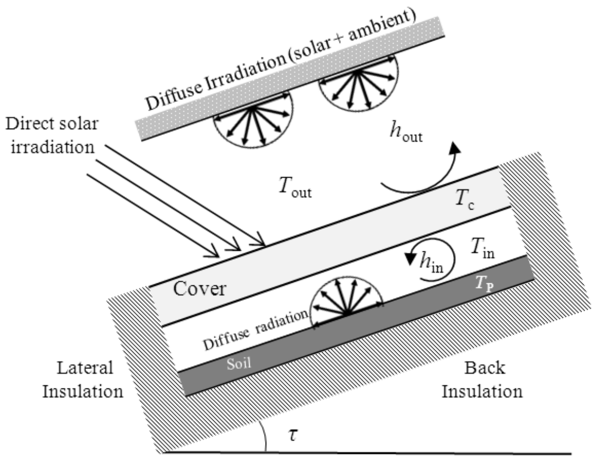

Fig. 4 Greenhouse system subjected to direct and diffuse irradiation

Chapter 5: Seasonal Assessment of Greenhouse Temperatures under Japan and Oman Climates

In this chapter, the seasonal effect on the temperatures of rectangular enclosures covered by three different materials, silica glass, PVC and LDPE, were experimentally assessed. Firstly, two field experiments were conducted in winter and summer to find the effect of the seasonal conditions on the thermal performances of the three rectangular enclosures. Similar to the experiment in chapter 4, the measured temperatures were compared to the simulated temperatures using the nongray rigorous model by REM^2. There were good correlations between the measured temperatures and the corresponded ones found by the rigorous model. Furthermore, there was a good agreement between the calculated and measured internal convective heat transfer coefficients. Figure 5 reveals the comparison of the measured and calculated temperatures for the enclosure (greenhouse) covered with a greenhouse in winter and summer experiments. The difference in inside air temperature, between the silica glass enclosure and LDPE enclosure were 8.3±2.1°C and 14.2±4.0°C for winter and summer experiments, respectively. These differences were due to higher transmissivity of LDPE material to IR radiation. Additionally, the transmissivity of glass material was higher. On the other hand, the differences in Tin were found lower between the silica glass and PVC enclosures; 2.8 ±2.2°C and 2.4 ±1.8°C for winter and summer experiments, respectively.

Jan. 10th , 2013 Jun. 24th , 2013

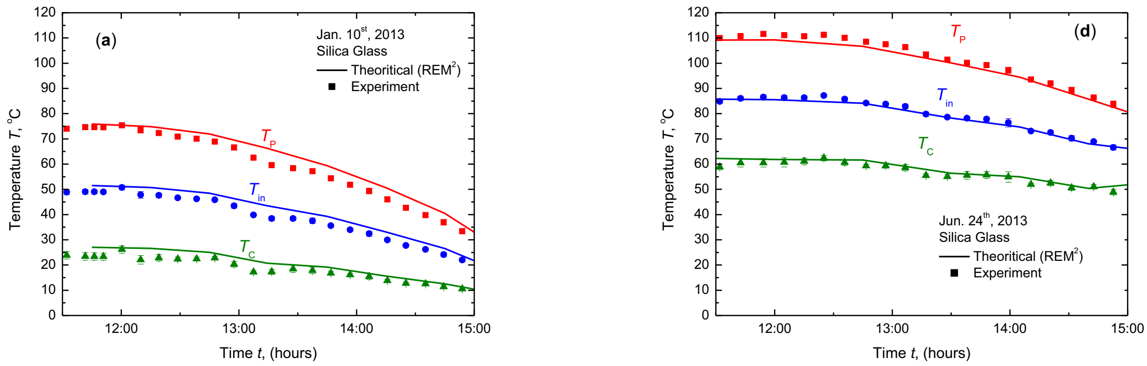

Fig.5 Temporal calculated and measured greenhouse temperatures for two experiments

According to noon time conditions, the enclosure temperatures, cover, inside air temperature and black ground temperature, were found higher in summer than winter. This was due to the smaller incidence angle, higher ambient temperature and lower convective heat loss at the external surface of the covering materials. For both field experiments, the inside air temperature measurements of the enclosure (greenhouse) covered by the silica glass showed the highest noon-time values followed by PVC and LDPE, respectively

Finally, a seasonal effect on noon-time greenhouses temperatures are going to be studied. Here, the meteorological data of Sendai and Muscat cities were acquired for different seasons. This information was used as simulation ambient conditions. In addition, the solar incident angles were predicted for different assessment period using the conventional methods. The results showed the effect of ambient temperature in different seasons due to different geographical locations. The ambient air temperature played a major rule in rising the greenhouse temperature in Muscat in contrast to Sendai city.

Chapter 6: General Conclusions

In this chapter, the main conclusions of this study were e emphasized in four main points. Firstly, applying the nongray rigorous model could help in determining the thermal performance of different greenhouse covering materials. Secondly, variation in inside air, soil and covering temperatures could be found for greenhouses that were covered with different materials. Thirdly, the contribution of greenhouse effect on rising greenhouse temperatures was verified. The seasonal and geographical effects on greenhouse temperatures were experimentally and theoretically examined.

論文審査結果の要旨

温室用被覆材は農業用温室などに広く用いられる半透明材料であり，温室における保温性能を評価する上でそのふく射伝熱を明らかにすることは重要である。また，被覆材による温室効果におけるふく射伝熱および対流伝熱の寄与については長い間議論されており未だ決着がついていない問題である。本研究では半透明媒体中のふく射伝熱の理論を用いて，温室用被覆材のふく射物性およびふく射伝熱を評価し，温室効果の定量的な評価を行っている。本論文は，これらの研究成果をまとめたものであり，全編6章からなる。

第1章は序論であり，本研究の背景，目的および構成を述べている.

第2章では，半透明媒体におけるふく射伝熱の理論を述べている。さらに，光線放射モデルによるふく射要素法を用い，太陽光に曝される半透明膜のモデル化を行っている。本モデルにより短波長の紫外線領域から長波長の赤外線領域までを統一的に解析することが可能になり有用である。

第3章では，市販されている様々な温室用被覆材に対し反射率および透過率の分光計測を行い，複素屈折率を逆問題解析により算出し，ふく射物性を評価している。さらに透明性導電膜の赤外線領域でのふく射物性を明らかにした。これらの成果は温室用被覆材の紫外線領域から赤外線領域までのふく射の吸収・反射特性を明らかにした点で有益である。

第4章では，様々な温室用被覆材の保温性能を実験及び数値解析により評価している。第3章で算出したふく射物性を用いた数値解析と実験結果が良好に一致し，両者の妥当性が示されている。これらの結果より温室効果におけるふく射伝熱の寄与を定量的に明らかにしている。これらの成果は、歴史的に長らく議論されてきた温室効果におけるふく射伝熱の影響を説明しており重要である。

第5章では，温室用被覆材の保温性能に及ぼす太陽高度や気温などの季節の影響を実験および解析により評価している。さらに太陽高度の地理的な影響も評価している。この成果は、温室を運用する上で被覆材の選定に活用でき、実用上有益である。

第6章は結論である。

以上要するに本論文は，温室用被覆材における紫外線領域から赤外線領域までのふく射物性およびふく射伝熱を明らかにし，温室効果の定量的な解明を行ったものであり，機械システムデザイン工学および環境工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。